A COMMUNITY-DRIVEN, NORTH AMERICAN DISTURBANCE RECORD AND PROCESSING SYSTEM FOR LAND SATELLITE DATA

[Note 11/2003: This is the original proposal submitted to NASA for the LEDAPS activity. Only a portion of what was proposed here was ultimately funded. Specifically, the Lidar processing and data distribution through UMCP were not included in the final project]

TABLE OF CONTENTS

(C.V.'s, current/pending support, and letters of commitment follow)

ABSTRACT

The US Global Change Research Program has defined an urgent need for a North American land-cover change and disturbance record to support investigations of the carbon cycle. We propose to develop, validate and distribute a high-resolution, 30-year record of (i) surface reflectance and (ii) vegetation disturbance and recovery by processing the North American Geocover Landsat record (1975-2000). In order to support future work integrating land-cover change information with vegetation structure, we will also repackage, coregister, and distribute GLAS lidar waveforms in a format convenient for terrestrial researchers. Satellite products produced by other efforts (AVHRR, MODIS), as well as ancillary data products (SRTM topography, forest inventory data) will support the proposed processing chain. These products will be developed and evaluated in close collaboration with the carbon cycle science community through a series of public workshops and the contributions of a Science Working Group. By capitalizing on the existing MODAPS data processing infrastructure, we can extract the scientific value from the Landsat archive in a manner that is both cost effective and responsive to the needs of the science community.

1.0 SCIENCE RATIONALE AND USER COMMUNITY NEEDS

The earth is warming. Weather station records and ship-based observations indicate that the global mean air surface temperature increased by 0.4 ^{o} - 0.8 ^{o} C in the 20th century (Watson et al., 2001). This trend reflects an imbalance between the forces that warm the planet - including greenhouse gases - and forces that cool it - reflective aerosols and clouds. Calculations by Hansen et al. (1998) implicate the increase in atmospheric CO_2 from 1850 to 2000 as the major forcing for warming with CH_4, CFC's and tropospheric ozone as additional significant contributors.

Anthropogenic emissions of CO_2 from fossil fuels have increased rapidly since 1850, currently amounting to a flux of about 7 Pg C per year to the atmosphere (Schimel, 1995). Throughout this period, both the terrestrial and marine environments have responded by absorbing more carbon, removing over half of these anthropogenic carbon emissions. Analyses of spatial and temporal variations in the atmospheric CO_2 records have suggested that the sinks are located at latitudes above 40 ^{o} N (Tans et al, 1990, Denning, et al., 1995, Ciais, et al, 1995, Bosquet et al, 2000). These studies further implicate the North American land area as a major sink averaging 1 to 2 Pg C /yr or about 15 to 30% of the anthropogenic CO_2 flux from fossil fuel burning. However, the exact location and processes by which the carbon is removed are not well understood, nor is it understood how long this rate of sequestration can be sustained in the face of climate change.

Forest-cover conversion, disturbance, and recovery have been proposed as primary mechanisms for transferring carbon between the land surface and the atmosphere, but the area and timing of these processes is still poorly quantified. Disturbance refers to a temporary reduction in ecosystem biomass followed by a recovery period (e.g. burn events, insect damage, logging, etc), while forest-cover conversion represents a permanent (or at least long-term) change in land-cover type and hence ecosystem properties. For the coterminous United States, Pacala et al.

(2001), estimated a sink of between 0.30 - 0.58 Pg C /yr, about half of which may be forest regrowth from disturbance and past land-cover clearing. These estimates of forest regrowth were based on ground samples of biomass from 1977 to 1992 from the US Forest Service, and the authors were only able to bound this carbon flux component between 0.11 and 0.15 Pg C /yr, an uncertainty of about ±25%. In the southwestern U.S., the progressive replacement of grasslands with herbaceous and forest biomass ("woody encroachment") may contribute a sink of some 0.13 Pg C/yr, although the uncertainty on this estimate is large since the actual area of encroachment is essentially unknown (Pacala et al., 2001). In Canada, Chen et al. 2000, estimates that during 1930-1970 lower disturbance rates, in combination with forest regrowth in areas disturbed in late nineteenth century, created a sink of 0.10 - 0.20 PgC/yr (Fig. 1). The increased disturbance during 1980-1996 released 0.06 PgC/yr. However, forest regrowth from this disturbance may currently contribute a small sink of 0.05 PgC/yr.

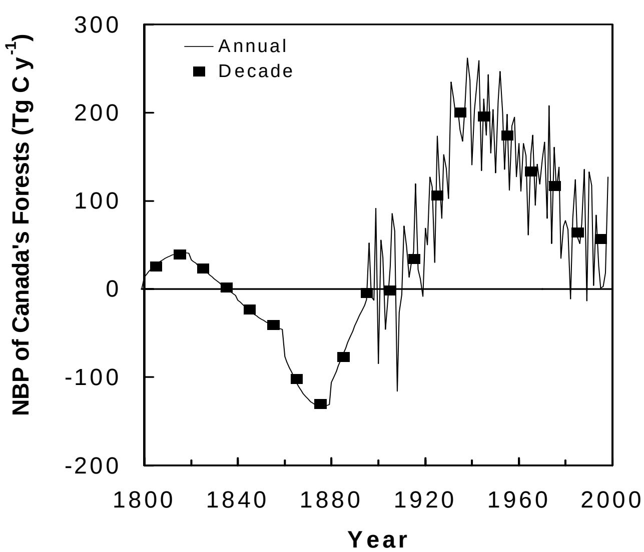

Figure 1. Net biome productivity (NBP) in Canada's forests for the last two decades, Chen et al., 2000.

The uncertainties in the location and mechanisms underlying the North American carbon sink and its response to future climate change has led the United States Global Change Research Program (USGCRP) to call for a program of carbon cycle research, focused on North America, to address the following questions:

- *What has happened to the CO_2 that has already been emitted by human activities?*
- *How do land management and land use, terrestrial ecosystems and ocean dynamics, and other factors affect carbon sources and sinks over time?*
- *What will be the future atmospheric CO_2 concentration resulting from environmental changes, human actions and past and future emissions?*

This program, the North American Carbon Program (NACP-Wofsy and Harriss, 2002), is an integrated program of satellite, aircraft and ground measurements and modeling to estimate the size of the NA carbon budget and understand the underlying processes. Given the uncertainties in the land-cover carbon fluxes presented above, the science plan for the NACP (Wofsy and

Harriss, 2002) has specified the need for satellite estimates of North American disturbance and recovery, and land-use and land-cover change, which could improve the accuracy of and periodically update the USFS ground-based estimates. **However, the capability to produce these satellite products on a routine and cost-efficient basis does not exist**, even though the satellite data and algorithms to do so have existed for nearly 30 years.

What is lacking? The 30-year Landsat record, needed to resolve and measure disturbance patterns, has yet to be assembled into a calibrated, atmospherically corrected, and consistently gridded format needed to automatically process these data. Without a radiometrically consistent data set, land cover signatures vary from frame to frame and from year to year, forcing regional and continental data sets to be processed one frame at a time. However, NASA, through a commercial data buy from Earth Satellite Corporation, has assembled a thirty-year, orthorectified global Landsat data set (but not calibrated or atmospherically corrected). This effort is scheduled for completion in the Summer of 2003. Secondly, in December 2002, NASA plans to launch ICESat with a Geoscience, Laser Altimeter (GLAS) that will, for the first time, permit the direct measurement of vegetation height potentially to 10 cm (although there are no funds allocated to process GLAS data to obtain vegetation height). These two developments open the way to apply radiometric algorithms to process the Landsat data to surface reflectance, place it onto a common grid with other land data to map disturbance, and combine it with GLAS vegetation height data to estimate canopy height and biomass density.

We propose therefore, to develop, validate, and distribute a high-resolution, 30-year record of North American forest change and disturbance by processing the 1975-2000 Landsat record to surface reflectance, and then evaluating change from the reflectance time series. We will also obtain the GLAS waveform data and co-register them with the other land satellite data to provide a foundation for obtaining a biomass change record in the future. **The integrated Landsat and GLAS records proposed here will open the way for subsequent work in biomass recovery and carbon flux analysis since the underlying data sets will already be available**. We will also utilize satellite products produced by other efforts, such as the AVHRR record extending to 1981, the SeaWiFS record extending to 1997 and the more recent MODIS record to aid in the analysis of the Landsat record. These products will be developed, validated and distributed in response to requirements obtained by close collaboration with the carbon science community. Such data, if integrated and easily accessible, would be widely used, by the science and applications communities funded by NASA, NOAA, DOE, USGS, USDA and other agencies participating in the US Global Change program. Of equal significance, by building the infrastructure for cost-effective, automated processing of Landsat data, the creation of science products at continental scales from this national resource will become routine.

2.0. PROJECT OBJECTIVES

The effort proposed is a collaborative multi-agency, international project among NASA, the USDA, the CFS, Colorado State University, and University of Maryland to:

- Produce and distribute for North America a Landsat surface reflectance time series, maps of forest-cover change and disturbance since 1975, and coregistered GLAS waveform data.
- Develop, implement, and validate algorithms to generate these products in collaboration with the carbon modeling and remote sensing science communities.

- Evolve the MODIS Adapative Processing System (MODAPS) to support automated Landsat processing in a manner consistent with NPOESS Prepratory Project (NPP) continuity requirements to generate integrated Landsat SR for continental North America.
- Providing the basis for future biomass change analysis by co-registering the proposed products with AVHRR, SeaWiFs and MODIS land SR time series generated outside this effort.
- Distribute all data products and documentation through a web-accessible interface, in formats suitable for carbon modeling.
- Promote software reuse and information system interoperability as part of the NASA SEEDS initiative.

The NASA Earth Science Enterprise (ESE) programs are carefully designed to address a specific set of questions regarding how the earth is changing, the primary causes of those changes, the Earth's response to natural and human-induced change, the consequences to life and our ability to predict them. Achieving our project objectives addresses in a direct way several of these ESE questions:

* How are global ecosystems changing?
* What changes are occurring in global land cover and land use, and what are their causes?
* How do ecosystems respond to and affect global environmental change and the carbon cycle?
* What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
* How well can cycling of carbon through the Earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane?

3.0. USER COMMUNITY INVOLVEMENT

As noted above, the carbon cycle science community represents the main "customer" for our proposed effort, although our product suite will be valuable to a broad community of science and applications users. The need for North American land cover/land use change and disturbance products has emerged from a number of community workshops, including the NACP planning activities and a series of NASA workshops held to define NASA's future role in the interagency carbon cycle effort (Wofsy and Harriss, 2002; McClain et al., 2002). The Landsat Global Data Working Group chaired by Dr. Anthony Janetos of the Heinz Institute also highlighted the need for land-cover analysis of the Landsat Geocover product, and recommended that such an analysis proceed on a regional or continental basis using local expertise. This proposed project represents an effort to meet the needs described by these workshops.

We will continue to maintain community involvement to ensure that our data products and services meet the needs of the carbon science community. Specifically, we will hold twice-yearly workshops open to the science community and conduct monthly teleconferences with a Science Working Group (SWG) that we will select at the outset. The workshops will provide an open forum to comment on the quality and usability of the products, and to propose new ideas for algorithm development. The SWG will consist of chairpersons representing the carbon modeling community, the remote sensing algorithm community, as well as our US agency and international partners. The SWG will be chartered to chair the science community workshops, summarize user feedback, review algorithm validation results, and formally recommend changes to processing algorithms or science products. In addition, we will continue our regular involvement with both NACP and NASA Carbon Cycle planning activities.

Through these mechanisms the user community will recommend changes to data products as well as satellite processing approaches and algorithms. Algorithms and data sets will be implemented in modular fashion on the processing system to permit testing of alternate approaches recommended by the community. Algorithm code itself will also be made available to the community. A validation program (see section 6.0) will also be implemented to test and evaluate alternate scenarios.

Beyond the carbon modeling community, other users and agencies will use the data products and processing approaches developed here. For example, the USDA-Agricultural Research Service (USDA-ARS) needs automated techniques to rapidly classify crop type and land-use within agricultural regions (see 4.6 below). Similarly, the Canadian Forest Service EOSD (Earth Observation for Sustainable Forests) program has committed to mapping all Canadian forests for the year 2000. These activities are synergistic with the proposed effort, and represent additional, known user communities for our products.

4.0. SCIENCE PROCESSING AND PRODUCTS

4.1. Science Product Philosophy

Our plan to use the science community's "best practices" algorithms to generate initial versions of each product, and then refine these algorithms based on our own validation activities as well as community feedback. In the sections below we propose initial algorithms for surface reflectance and disturbance mapping, based on our experience and knowledge of published approaches. It should be emphasized, however, that defining product characteristics and algorithms will be an iterative process, and will depend on a continual dialog with the user community through the workshops and Science Working Group described in Section 3.

All products will first be implemented and validated on a regional basis ("Beta" products, Table 1), and then extended to North America with increasing maturity ("Provisional" and "Validated" products). However, we also recognize that reprocessing and validation will be a continous cycle, and we have designed our processing system to support several cycles of reprocessing each year. Reusing the existing MODIS Adaptive Processing System (MODAPS) makes feasible the rapid, automated analysis of the Landsat archive in the same manner as MODIS or other EOS data streams. Although large-area, "handcrafted" analysis of Landsat imagery is certainly possible (e.g Skole and Tucker, 1993; Chomentowski et al., 1994), by automating and speeding the analysis we can support continuous improvements in accuracy and usability through reprocessing.

In the sections below, we first describe the "input" data sources required for the processing stream, and then outline our initial algorithms to convert these raw data into reflectance and disturbance products. We also discuss the proposed geolocation and repackaging of GLAS waveform data, and outline our collaboration with the USDA-ARS to assess the use of Landsat surface reflectance data to map soil carbon fluxes in a series of test sites, another important component of the NACP.

4.2. Data Sources
The surface reflectance and land-cover change/disturbance products will rely on the Landsat data record. Specifically, we will use the Geocover data sets produced by Earth Satellite Corporation as part of the NASA Science Data Purchase program. The Geocover data are global collections of full-resolution, radiometrically unaltered Landsat MSS, TM, and ETM+ scenes, orthorectified, and centered on the years 1975, 1990, and 2000 (within ~3 years). Thus, the Geocover product can provide a decadal view of how global land-cover conditions have changed during the last 30 years. Individual scenes were selected to minimize cloud-cover and record peak greenness for local vegetation. Since the same ground control library is used for processing both the 1990 and 2000 collections, relative (image-image) geodetic precision should be within 1 pixel, making this data set ideal for radiometric change detection (J. Dykstra, personal communication).

Vegetation structure can be derived from the ICESat GLAS (Geoscience Laser Altimeter System) instrument, to be launched in December, 2002. The GLAS instrument is a full return orbital lidar, with laser wavelengths of 1064 and 532 nm. Individual samples integrate a spot size of ~70 meters on the ground, and samples are spaced every 170 meters along track. While the primary use of GLAS is to obtain ice sheet topography, recent work has demonstrated that GLAS can also be used to map canopy height in regions of low to moderate topographic relief (Lefsky et al, 2002).

Ancillary data that may be required for processing include vegetation phenology from coarse resolution sensors (AVHRR, SeaWiFS, MODIS), SRTM digital topography, and long-term climate databases (e.g. NCEP).

4.3. Landsat Normalized Surface Reflectance Product
Until the EarthSat Geocover dataset can be rendered to a consistent surface reflectance product, generating land-cover change or disturbance maps will have to proceed scene-by-scene since land-cover types can have different spectral signatures in each image. By placing the Landsat observations into the common physical basis of reflectance, automated and rapid analysis of the dataset becomes feasible and cost-effective (Masek et al., 2001).

We propose to produce a uniform surface reflectance product for North America in each of the three decades using the processing flow shown in Figure 2. Landsat surface reflectance products will be produced and distributed at a resolution of 30-meters for TM and ETM+, and 60-meters for MSS. In addition, some validation scenes will be aggregated to resolutions of 250 and 500-meters, to compare results with corresponding MODIS surface reflectance products. The project will also ingest additional Landsat scenes from the community as resources permit, and convert these scenes to surface reflectance.

For Landsat-5 TM and Landsat-7 ETM+, where reliable calibration coefficients exist (Teillet et al., 2001), each image will first be calibrated and converted to top of the atmosphere (TOA) reflectance. Masks for clouds, cloud shadow, and snow/ice will be prepared for use in later processing steps. For TM and ETM+ data, clouds will be identified using the Landsat ACCA algorithm (Irish, 2000). Cloud shadows will be masked by translating the existing cloud mask a scene-specific horizontal offset along the solar azimuth direction (a function of cloud height, which will be estimated from the spatial anti-correlation with cloudy pixels or from NCEP data).

Several empirical techniques have been proposed for removing atmospheric haze from Landsat imagery (Chavez, 1996; Moran, 1996; Song et al., 2001). Initially we will focus on atmospheric correction methods based on radiative transfer theory. With rare exception, all of the available RT-methods for Landsat atmospheric correction (Vermote et al., 1997; Ouaidrari and Vermote, 1999; Liang et al., 1997) make use of the dark dense vegetation (DDV) method of Kaufman et al. (1997) in order to extract aerosol optical thickness from the imagery. Based on the physical correlation between chlorophyll absorption and bound water absorption, the DDV method suggests a linear relation between shortwave-infrared surface reflectance (nearly unaffected by the atmosphere) and surface reflectance in the blue and red bands. By using this relation to calculate surface reflectance for the visible bands, and comparing the result to the TOA reflectance, aerosol optical depth may be estimated. Although the actual coefficients of these relations may vary somewhat, the absolute error over selected dark targets is small. Wen et al. (1999) generalized the DDV approach to use scene-dependent coefficients rather than prescribed coefficients.

Having estimated aerosol optical thickness for TM and ETM+ data, we will implement and compare two approaches for retrieving surface reflectance. The “traditional” methodology uses 1-D radiative transfer models (e.g. 6-S) to calculate surface reflectance from Landsat radiance, similar to the approach currently being used for MODIS (Vermote et al., 1997). A new methodology (supported by the Landsat Program Office), is based entirely on a new radiative transfer theory (Lyapustin and Knyazikhin, 2002) which incorportates both 3-D and surface anisotropy effects. The initial validation against AERONET data shows that aerosol retrievals with the new method are free of systematic bias that can affect 1-D retrievals over dark targets. Using a library of Bi-Directional Reflectance Function (BRDF) shapes for different land-cover types, the algorithm can also normalize surface reflectance imagery to a constant solar zenith angle (Lyapustin and Kaufmann, 2001).

Since older MSS data cannot be reliably calibrated or atmospherically corrected, each scene from the 1975-era MSS archive will be radiometrically rectified to the ETM+ image as in Hall et al. (1991a). A tasseled cap transformation (Kauth and Thomas, 1976; Crist and Cicone, 1984) applied to TM and MSS imagery can be used to identify invariant (minimum greenness) dark and bright targets for each image, independently. By regressing the TOA reflectances of the MSS invariant targets (ITs) against those of the TM or ETM+, a scene-specific relation can be derived for rectifying each MSS image to surface reflectance. This algorithm was tested thoroughly during FIFE (Hall et al., 1992) and BOREAS (Hall et al., 1997) field experiments and produced good results. Data quality checks will be conducted to ensure that processing is proceeding as planned, with some potential for manual intervention to handle unusual frames. We will also explore the possibility of radiometrically rectifying both the MSS and TM scenes to the ETM+ imagery, in case the existing Landsat-5 calibration does not prove sufficiently accurate for reliable change detection. Other approaches for rectifying Landsat imagery also exist. For example, Schott et al. (1988) and Chavez and McKinnon (1994) suggested using histogram normalization techniques, in which the histogram of the entire image is “matched” to the histogram of a reference image. We will explore these alternative approaches on an as-needed basis, as determined by the results of validation activities and user feedback.

Results from the land-cover change processing will likely inform future changes in the surface reflectance algorithm. For example, although most GeoCover scenes were acquired on near-anniversary dates, we may find that residual variations in topographic illumination affect the apparent distribution of disturbance in mountainous terrain. In this case, we will explore integrating an additional step to correct for topographic illumination (e.g. Ekstrand, 1996; Gu and Gillespie, 1998).

The algorithm flow described here (and shown in Fig. 2) has already been implemented in prototype form, and integrated into the MODAPS processing chain. Prototyping the SR algorithms on MODAPS allowed us to assess the algorithm's performance, understand the data flow and calibration issues, determine how easily MODAPS could be tailored to process Landsat data, and better estimate the required computing resources.

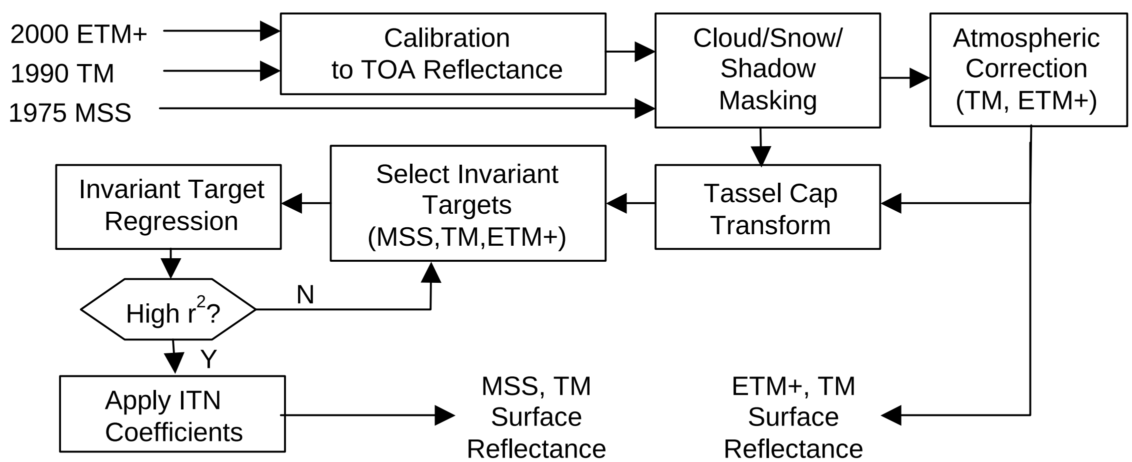

Fig 2: Landsat surface reflectance algorithm.

4.4. Landsat Disturbance/Forest-Cover Change Product

Our objective is to satisfy the goal of the USGCRP to reduce uncertainties in the land-atmosphere carbon flux related to disturbance, recovery, and forest-cover conversion (Pacala, 2001; Wofsy and Harriss, 2002). The approach is to create maps of change or disturbance, for specific processes of recognized importance to the North American carbon cycle (Table 1). The resulting product will consist of multiple layers – one for each change or disturbance process that occurred during the "change interval" (e.g. 1975-1990 or 1990-2000) for a particular path-row location. As an initial concept, we see four data layers: deforestation, afforestation, burn scars and undifferentiated disturbance. The first two represent long-term land-cover conversion processes, while the last two represent cyclic disturbance processes. The "undifferentiated" category is intended for forest disturbances that cannot be reliably classed as a particular type (e.g. logging, insect defoliation, wind throw, etc.).

A variety of approaches for mapping forest-cover change and disturbance from Landsat data have been published during the last 25 years (e.g. Malila, 1980; Townshend and Justice, 1988;

Hall et al, 1991b; Skole and Tucker, 1993; Hall et al, 1994; Collins and Woodcock, 1996; Tucker and Townshend, 2000; Hayes and Sader, 2001; Cohen et al., 2002). By starting with a consistent surface reflectance record, automating processing procedures, and integrating coarse-resolution data sources (AVHRR, MODIS), we can extend these approaches to produce a consistent, continental view of forest-cover change and disturbance. This record can then be used in carbon models to estimate carbon emissions for disturbance or carbon uptake for regrowth, or, in the future, by integrating lidar-based measures of vegetation structure to derive biomass change directly.

In later years, we intend to add an additional category for woody encroachment, which has been highlighted as a potential carbon sink but has never been comprehensively mapped (Pacala et al., 2000). We will use the Landsat data series to estimate the extent of this woody encroachment and its change over time. To estimate the actual change in biomass density, a variety of spectral mixing/unmixing approaches are being tested for mapping the fractional cover of woody biomass from Landsat data , (Hall et al., 1995, 1996, Peddle et al., 1996; Bateson et al., 2000). As these techniques mature we will work with the community to incorporate them for woody biomass assessment

Table 1: Land disturbance/change processes significant to the carbon cycle

Disturbance Process	**Geographic Distribution**	**Initial Mapping Approach**
Deforestation	Eastern US, NW US	Radiometric change detection
Afforestation	Agricultural regions	Radiometric change detection
Logging and regeneration	Boreal, SE US, NW US	Radiometric change detection; incorporation of forest inventory stats
Fire	Boreal, Western US	Radiometric change detection; merge with AHVRR/MODIS stream
Woody Encroachment	SW US, Canadian rangeland	Radiometric change detectionfor area; spectral unmixing for biomass

Mapping deforestation and afforestation will follow the criteria described in the Global Observations of Forest Cover / Land-Cover Dynamics (GOFC-GOLD) Fine Resolution design for mapping forest-cover change. Since the spectral characteristics of mature forests are relatively distinct, we believe that a generalized algorithm can be used to map forest-cover conversion across most of North America. The remote sensing community has found good results from radiometric change-detection approaches, such as change-vector analysis (Malila, 1980; Colwell and Weber, 1981; Johnson and Kasischke, 1998; Zhan et al., 2000) and multi-date image classification (Jensen, 1996). Mapping afforestation will present some additional challenge, since the spectral characteristics of young forests can be confused with other land-cover types (e.g. crops). In some cases, it may be necessary to adjust the algorithm to values specific to a particular biome or region. We will first stratify North America into ecoregions. Collaborators will then work within these mapping units to adjust algorithm parameters on a regional basis to improve mapping consistency. An example of this approach is shown from recent work on forest-cover change in Northern China (Fig 3, Masek et al., in prep).

Developing and recommending approaches for mapping fire scars will be the primary responsibility of Canadian collaborators at the Canadian Forest Service, who have extensive experience in these techniques. The utility of Landsat-type data for mapping burn scars is well known, and a number of radiometric change detection techniques for mapping recent and revegetating fire scars have been published (RussellSmith et al., 1997; Steyaert et al, 1997; Koutsias and Karteris, 2000; Michalek et al, 2000; Garcia-Haro et al., 2001). Mapped scars will then be correlated with the Canadian Large Fire Database (LFDB) and the AVHRR 4-km GAC archive to establish the timing of specific fire scars since 1975. For some smaller scars, no record is to be expected from the fire database or the AVHRR record (due to resolution and/or cloud-cover). For a subset of these cases, detailed semi-annual series of Landsat imagery will be acquired to verify the existence and timing of the fire. As the burn scar algorithm is perfected for the Boreal region, we will extend its use to the United States on a provisional basis.

This work will also capitalize on existing efforts, such as the Canadian Forest Service (CFS) EOSD program and the USDA Forest Service Forest Inventory and Analysis (FIA) program, which are actively investigating ways to improve monitoring of North American forest resources. Together this partnership can provide invaluable expertise in generating disturbance mapping algorithms, particularly for fire and logging disturbance, and capitalize on the existing forest inventory data for validation and training. Our effort in turn will benefit USDA-FS and CFS programs though the access provided to the 30-year Landsat Geocover surface reflectance data set and the derived disturbance products as well as to the surface reflectance and disturbance processing codes, change detection methods etc. In addition, some processing capacity will be available on the Landsat/MODAPS system for selective processing of additional frames to suit particular USDA-FS and CFS needs.

We will generate the forest-cover change and disturbance layers at 90-meter resolution, in order to limit errors due to residual misregistration of Landsat scenes (Townshend et al., 2000). Coarse-resolution gridded products (0.05-0.5 degree resolution) will be aggregated from these high-resolution maps for carbon modeling and other large-area applications. Gridded products will represent a statistical aggregation of the disturbance maps, with each cell recording the percent-of-area disturbed or converted, and the mean rate of disturbance and conversion for the periods 1975-1990 and 1990-2000.

Fig. 3. Example of disturbance mapping from Changbai region, NE China, a mountainous region with small-scale plantation forestry: May 1991 Landsat-5 TM image (left); September 1999 Landsat-7 ETM+ image (center); forest clearing (red) and forest regrowth (green) (right). Each image is ~15 km across. Analysis used spectral angle change detection approach, operating on atmospherically corrected surface reflectance imagery, similar to the methodology discussed here (Masek et al , in prep).

4.5. GLAS Enhanced Waveform Product

The existing level 2 data products being produced by the GLAS team are appropriately focused on applications in atmospheric science and the topographic mapping of ice, ocean and land surfaces. To support the development of GLAS analysis algorithms within the terrestrial science community, we will repackage and distribute GLAS full-return waveforms for North America with co-located topography and Landsat-7 ETM+ surface reflectance measurements.

The purpose of repackaging the existing GLAS data structures is to create a product that those concerned with the height of terrestrial vegetation can easily use to analyze the height and biomass of aboveground vegetation. The existing level-2 land altimetry product (GLA_14) does not include the raw waveform data, but rather the coefficients for a series of Gaussian fits to the data. While initial simulations indicate that these coefficients can reproduce the original waveforms with good accuracy, it is unclear whether this will be true for complex multi-modal waveforms. Therefore, we will add the original waveform data (available in the GLAS Level 1 GLA_01 product) to the existing GLA_14 land altimetry product, along with a series of calibration information, such as the vertical resolution of the digitized waveform, receiver gain setting, and characteristics of the outgoing laser pulse, which are necessary for full waveform analysis in land surface investigations. These waveforms will then be integrated with co-located ETM+ reflectance data and digital topography to aid algorithm development and validation.

Initial acquisitions of the GLAS data will occur through Dr. Harding's participation in the GLAS science team until that team's calibration/validation is finished, at which time the NSDIC (National Snow and Ice Data Center) will take over distribution of the data (Summer 2003). In addition to collecting all relevant variables into a single, simplified data structure, our repackaged data product will convert the GLAS one second data packets (composed of 40 laser shots) into an individual data structure for each laser shot, to simplify their use in GIS systems. In related work, two interfaces to our repackaged GLAS waveforms are already being built, in the form of a web database and ArcGIS extension. They will allow much easier initial browsing and selection of data within geographic limits, and an intuitive user interface for querying the downloaded data.

4.6. Agricultural Soil Carbon

US croplands constitute a large carbon pool but are currently in near carbon balance (Pacala et al. 2001). Currently there is roughly 150 Mha of cropland in the coterminous U.S. with soil carbon stocks on the order of 15–20 Pg C (Kern and Johnson, 1993), compared to the 60–80 Pg C total for all coterminous US ecosystems (Kern 1994, Waltman and Bliss 1997). Historically, conversion of native ecosystems to cropland resulted in a net loss of carbon, on the order of 5–6 Pg C. However, increased productivity and improved management practices e.g. residue management, reduced tillage intensity, increased productivity through genetic improvements, improved management inputs (fertilizer, pesticide, weed control) and intensified crop rotations (Paustian et al. 1997) have stabilized or begun to increase soil carbon uptake (Cole et al. 1993, Lal et al. 1998). Recent estimates of the potential for carbon sequestration in U.S. agricultural soils are on the order of 0.05–0.20 Pg C/year over the next 2–3 decades, based on the use of existing technologies, (Bruce et al. 1998, Lal et al. 1998). The range of these estimates reflects both uncertainties in carbon accumulation rates for different practices and soil/climate conditions and uncertainty in the projected rates and extent of adoption of carbon conservation practices. To assess carbon uptake trends from improving practice, data are needed on the area of carbon conserving management practices and any increase with time as input to biogeochemical cycling models.

Processed Landsat surface reflectance data, in conjunction with AVHRR, MODIS, and SeaWiFS imagery, will be used for studying land-use changes in croplands and their impact on crop production in the Midwest. Agricultural soils in North America have the potential for sequestering large quantities of carbon, but as noted above, there is considerable uncertainty as to the future trajectory of this sink. The USDA-ARS Hydrology and Remote Sensing Laboratory is studying changes in soil organic matter (SOM) over the past 30-years at selected sites in the U.S. Corn Belt. These sites are selected on the bases of soil properties, crop type, rainfall distribution, and management practices. A GIS database is being developed with historic data on climate, soils properties, and crop management to provde the bases for simulation of annual SOM changes using biogeochemical models. The Landsat surface reflectance timeseries generated here will support characterization of land-use changes in and around these sites, providing a mechanism to scale up the simulations to regions of interest. A better understanding of the changes in SOM will be instrumental in planning future management practices within the Corn Belt.

5.0 INFORMATION TECHNOLOGY APPROACH

We propose to tailor the MODIS Adaptive Processing System (MODAPS) to automate the processing of more than 1500 Landsat scenes to create co-registered radiometrically and atmospherically corrected products for North America. MODAPS is a modular system with components for ingesting ancillary products and instrument data, generating and archiving science products, and distributing these products to archive centers and science team members. Each day the MODAPS produces and distributes over 2TB of land, ocean and atmosphere products for the MODIS instruments on the EOS Terra and Aqua spacecraft (Justice et al., 2002). These data are sent to Distributed Active Archive Centers (DAACs) for archiving and distribution to the public. An additional 300GB is shipped to scientists for quality assurance, product validation and for fusion with products from other missions over global study sites. MODAPS is also being tailored to meet the processing, archiving and distribution needs for the OMI (Ozone Monitoring Instrument), which will be launched on the EOS Aura spacecraft in 2004.

The modular architecture of the MODAPS, illustrated in Figure 4, allows developers to easily tailor the system by replacing any sub-system, such as the Archiver, or sub-system component such as Legato Networker, with alternative software if desired. For the proposed effort sub-systems that handle job execution and near-line archiving (Scheduler, Archiver and the Operations Interface) will require only minor customization. Sub-systems which acquire and store input data sets or ship data products will be tailored to meet the needs of the specific Landsat and GLAS data sets and interfaces to data providers. These sub-systems include: Ingest, which will be modified to ingest Landsat Level 1 Geocover data from the UMD GLCF ESIP and

GLAS data from the National Snow and Ice Data Center DAAC, and Export, which will be modified to ship the higher-level Landsat and GLAS science data products to the GLCF for archive and distribution.

In MODAPS, data products are generated by Product Generation Executives (PGEs) which are launched and monitored by the Scheduler sub-system. The MODIS PGEs are programs written in C, Fortran 77 or Fortran 90 which are combined with the EOS Science Data Processing Toolkit (SDP-TK), which includes HDF support and routines that isolate science software from operating system calls to promote portability, and Perl scripts, which handle data staging for production runs. Most of the development effort for this project will be concentrated in the area of creating PGEs for Landsat reflectance and disturbance products that will run on the commodity processors used by MODAPS. As noted in Section 4.3, a prototype (including PGE’s) of Landsat processing in MODAPS was developed over the last three months and is beginning to produce a beta version of the land surface reflectance product.

The MODAPS hardware environment consists of a central production server, a set of low-cost compute nodes and a database server connected to a high-speed network. The central production server communicates with data providers and the data distribution sites through the Internet. Online disk storage used for distribution and the automated tape library used for storing products are connected to the central production server. Products are generated both on the central server and on compute nodes attached to the central server via Gigabit Ethernet. Each compute node is a two-processor system running Linux with sufficient memory and local storage to hold all input files, all output products and all PGEs required for processing. After processing products are copied to the central server, and then shipped to the GLCF and written to the near-line tape library. A database server maintains an overall picture of the production system, including the location of the product files, status of the jobs, etc. The Landsat and GLAS processing the system has been sized to hold an on-line copy of the entire input data set (about 1TB) and two versions of the output products (about 2TB) and allow the North American data set to be processed within a month. As noted in 4.1, the capacity to reprocess the data set several times each year and store two versions online will enable us to explore new algorithms from the community and evaluate the changes. In addition to the production system, an independent test system will be used to host one or more instances of MODAPS software that will be used for tailoring MODAPS and for algorithm development, testing, and quality assurance.

Beyond minimizing development costs and reducing risk, reusing the MODAPS system leverages a well-trained operations and sustaining engineering staff that is familiar with supporting production on the MODAPS system. We will also share staff for software development, configuration management, integration, testing and quality assurance of products with the MODIS team. Similarly, the MODIS approach to algorithm development, integration and testing will be reused for Landsat processing. This approach is currently being used to integrate over seventy MODIS algorithms from science teams located at NASA’s Goddard Space Flight Center and at universities throughout the world and has allowed the continual improvement in the quality of MODIS products.

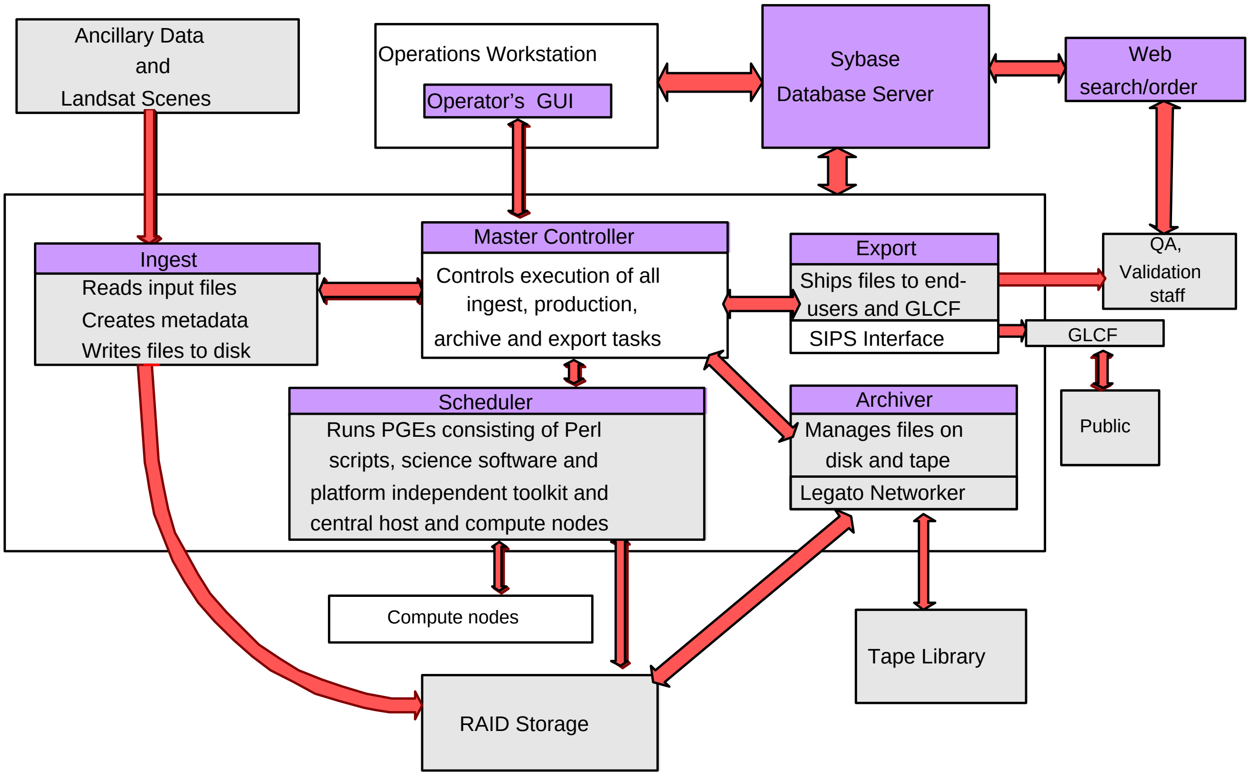

Figure 4: MODAPS hardware and software architecture

6.0 PRODUCT VALIDATION AND QUALITY ASSURANCE

6.1. Quality Assurance Approach

Both Quality Assurance (QA) and Data Validation form key aspects of our proposed work. Quality Assurance describes the processes used to guarantee the generation, archiving, and distribution of science products that are accurate, usable, and meet science needs. A major aspect of QA is Data Validation, which refers to the rigorous assessment of the accuracy of data products, and the documentation of known problems

Each algorithm will go through several stages in the development cycle, each stage improving in quality: from Beta to Provisional and then to Validated. Steps within each of these stages include: proposing a change the algorithm (or a new algorithm), coding and documentation of algorithm, producing a new data product, comparing the new product to the previously baselined algorithm, and documenting the changes to the. The Science Working Group and project scientists will work together to evaluate results and propose algorithm changes, with regular feedback from bi-annual user workshops. A web page will be used to keep the user community abreast of the status of the algorithms, known issues and production schedule.

In addition, inspections will assure that data production as implemented in MODAPS generates identical results to those intended by the algorithm developer. Before data distribution, project scientists will compare results for hand processed Landsat scenes with the same scenes processed by the MODAPS. Any discrepancies will be noted and tracked in an online database of known problems. Selected subsets of the production run will also be pushed to individual project scientist's facilities or computers for evaluation.

6.2. Landsat Reflectance Validation

Validating the Landsat surface reflectance algorithm will occur in three phases: (1) assessment of the TM/ETM+ atmospheric correction and surface reflectance retrievals, (2) assessment of the TM/MSS rectification procedure, and (3) understanding the utility of the 1975-2000 surface reflectance imagery for quantifying land-cover changes.

To assess the accuracy of the TM/ETM+ atmospheric we will first compare simultaneously acquired Aerosol Robotic Network (AERONET) observations with image-based aerosol optical thickness. Some 25 AERONET sites record aerosol properties throughout the United States and Canada, and several of these records extend back to the early 1990's (Holben et al., 1998). These records will be used as "ground truth" for comparing image-based aerosol retrievals. The accuracy of the overall surface reflectance retrieval for ETM+ will be assessed through comparison with MODIS and MISR surface reflectance products, and by using selected ground targets where the Landsat-7 science team has measured surface reflectance (e.g. Railroad Valley, NV; Maricopa Agricultural Center, AZ). For older imagery, comparisons will be made with data from the BOREAS and FIFE field programs, where surface reflectance was recorded from helicopter and ground observations. We will also perform an "ideal" atmospheric correction on small regions surrounding AERONET sites (where aerosol properties are available) in order to obtain additional surface reflectance validation data.

Assessing the image rectification approaches will rely on measures of spectral consistency through time for analyst-identified invariant targets (e.g. runways, parking lots, quarries), as well as spectral consistency for stable vegetated land-cover. For example, we will examine the rectified spectral reflectance trajectories for both regenerating stands and mature, undisturbed stands, to make sure that each follows known trends (e.g. Cohen et al., 1995). These trajectories will be extracted for a variety of locations (forests, mountainous regions, grasslands) in order to understand regional issues associated with the rectification methodology.

6.3. Land-cover Change and Disturbance Validation

One approach to validating satellite-based land-cover change algorithms is to compare the algorithm results with those found from manual interpretation higher-resolution data sources. For our application, we will select a series of small test sites, stratified by biome, and compare calculated rates of change and disturbance with those found by analyzing matched pairs of USGS Digital air photos and Ikonos satellite data. Through the NASA Data Purchase program, large amounts of Ikonos data have been archived at the Stennis Space Center for Earth Science research. When combined with air photos, long-term rates of land-cover conversion can be established at high resolution.

Additional validation will come from comparison with forest inventory data, which record the volume and area of timber harvested by county. The USDA-FS Forest Inventory Assessment (FIA) database includes attributes for some 125,000 plots across the United States. We expect a correlation between rates of harvest from FIA data and calculated disturbance rates for selected counties in the U.S. Disturbance maps will also be compared with the MODIS 250-meter land-cover change product. Although the MODIS change product only began production in 2000, the spatial patterns found in the 1990-2000 analysis should show some correspondence with those found in the MODIS analysis.

We also anticipate that some individual scientists will validate the disturbance products for local regions as part of normal scientific practice. As these experiences accumulate, and are passed to the Science Working Group, we will incorporate them into our product assessment.

7.0 DATA DISTRIBUTION AND CUSTOMER SERVICE

7.1. Active Data Archive

Distribution of data products during the life of the project will occur through the University of Maryland Global Land Cover Facility (GLCF). A member of the NASA ESIP Federation, the mission of the GLCF is to develop and distribute remotely sensed satellite data and products to the terrestrial science and applications community. The GLCF provides a full range of data and information services to users, including data search and download, data subscriptions, on-demand processing of AVHRR data, data brokering, and value-added processing of satellite imagery for land-cover applications. Current data holdings include MODIS land-cover change/vegetation index data, AVHRR-based land-cover and tree-cover maps, global Landsat imagery, the UMD Landsat Pathfinder tropical deforestation dataset, and data characterization layers for the EOS validation core sites.

This project will capitalize on current GLCF services for Landsat holdings. Users will be able to use the web-based Earth Science Data Interface (ESDI) to geographically search for full-resolution or gridded surface reflectance and disturbance products. They will then have the option of obtaining these data products for free via FTP, or on media (CD, DVD) for a nominal fee (currently $20US). In addition, a full range of documentation will be served for each product, including a format description document and metadata files. GLCF provides data in its own standard metadata format in addition to being compliant with a number of US metadata standards, including FGDC.

It should be noted that the UMD GLCF is also proposing to this announcement, and that their continued operation is dependent on future NASA funding. Should the GLCF fail to secure necessary funding, we will commit to distributing data products through a web-accessible interface to the MODAPS system via FTP and CD/DVD.

7.2. Long-term Archive and Distribution

We recognize the importance of maintaining geophysical datasets beyond the life of individual projects, and intend to work with the USGS EROS Data Center (EDC) DAAC to archive and distribute our surface reflectance and land-cover change/disturbance products beginning in 2008 (ie. after the conclusion of this project). We have included two milestones in our payment schedule to mark progress toward this goal. First, at the conclusion of CY2005, we will initiate formal discussions with the EDC DAAC to assess the utility of including these datasets in their holdings. This initial discussion will include a report from the Science Working Group assessing the scientific value of long-term archival for each product. We would then draft an agreement with the EDC DAAC to add the products to their archive. In fact, we have have already contacted Thomas Kalvelage, the EDC Land Processes DAAC Manager, and have obtained a initial statement of interest from him (see Letters of Support at the end of the proposal package).

8.0 CONTRIBUTION TO SEEDS EVOLUTION AND FEDERATION

This project embraces the ideals of NewDISS and SEEDS, which envision an ecology of interoperating information services, ranging from large ("backbone") providers of raw instrument data to Science Data Centers producing customized results for specific user groups. Rather than implementing a centralized approach to generate "standard" products, we wish to engage science users to guide the evolution of products through the life of the project. Our emphasis on continuous validation and reprocessing, public user workshops, a permanent Science Working Group, and distributed approaches to algorithm development are all examples of our commitment to realize the potential of SEEDS.

Project members have already participated in SEEDS workshops though presentations at plenary sessions and on study teams as representatives of the MODIS Science Team, the University of Maryland GLCF ESIP and the MODAPS Science Investigator-led Processing System (SIPS). At the workshops, we have contributed to the following study teams: Standards for Near-term Missions where we provided lessons learned from MODIS and discussed standards used in the development of the OMI data processing and products, Data Life Cycle and Long-Term Archive where we addressed issues of the long-term archiving of MODIS products, and Reference Architecture and Reuse Assessment where we discussed MODAPS reuse of open source software and tailoring of the MODAPS system to accommodate other satellite missions such as OMI.

We plan to continue participating in three SEEDS working groups at a level of 0.1 FTE each (0.3 FTE total) with costs shared between this effort, MODIS, and OMI. On the standards and interfaces group we will share lessons learned from working with the HDF-EOS formats and standards checking tools used to insure MODAPS science software meets EOS, MODIS and OMI guidelines. On the technology infusion working group, we can address lessons learned in creating flexible, scalable processing configurations that mix high-end UNIX servers with low-end Linux processors, using high-speed networking. On the architecture and reuse working group, we will share our experiences with reusing the MODAPS processing framework for multiple missions, replacing COTS software with open source packages, and releasing science software for reuse by the public.

Open architectures, software reuse and interoperability are important goals. We will pursue the development of Landsat algorithm PGEs as an open-source project to support community processing of Landsat data if warranted by community interest. Source code for Landsat processing will also be released for reuse by the community through the Goddard Direct Readout website, which handles distribution of MODIS PGEs to the community. Specific data formats for end-user products will be selected in consultation with our Science Working Group and GLCF. In particular, we wish to explore data formats that allow rich user services, such as distributed granule-level search and order across SEEDS providers.

METRICS

The project will track metrics required by the ESIP Federation and those specified in the CAN Announcement, and report them to NASA management on a quarterly or monthly basis. The UMD GLCF has also played a leading role in defining metrics for the ESIP Federation. We will obtain statistics from the GLCF on the number and volume of data products distributed, as well as direct user feedback regarding those products.

We will seek additional metrics to describe the quality and quantity of data products produced, the quality and capability of the information technology developed, and the value of our products to the carbon science community. Table 2 details the methods we will use to assess these questions. We will issue a survey to the data users, at six months and at yearly intervals after initial publication of products to assess technical usage, content utility and overall value of the collection to the research community. The intent here is to identify and quantify the activities which this data collection has enabled (i.e., new research areas, new research usage of data, educational usage, etc.).

Table 2: Project-specific Metrics

QUESTIONS	METRICS and/or ACTIONS
A. Are the data products of sufficient quality?	1. Publication of science validation results and Science Working Group reviews (ie. Overall assessment of product maturity, known issues, geographic biases, etc). 2. Publish “findings” and minutes from community workshops
B. How well is the MODAPS system performing?	1. Track rates of data throughput (and throughput per unit cost) during production runs; track number of open issues during MODAPS development and operations. 2. Track number of reprocessing iterations and marginal cost of product reprocessing.
B. Are the data sets useful to the ESE community?	1. Monitor the number and origin of the order for the data (hits on the web page and/or data orders). 2. Work with the modeling community to quantify impact of products on carbon flux models (e.g. North Am. terrestrial NEP with vs. without integration of disturbance product) 3. Questionnaire-based survey of users who have acquired data to inquire about their usage and data utility.
C. Does the use of the data further earth science?	1.Questionnaire-based survey of users who have acquired data to ask about impact of data set on their research. 2. Track numbers and types of publications citing the data products. Assess relation of published research to ESE Earth Science questions.

MANAGEMENT APPROACH

This team is uniquely qualified to carry out the proposed work, and brings a wide range of personal and institutional strengths in the areas of remote sensing, data processing, product validation, and biospheric sciences. From NASA’s GSFC, the project includes representatives from the Landsat Project Science Office, the GLAS science team, and the MODIS processing and validation teams. Participants from CFS and USDA-FS bring expertise in merging of remote sensing data with forest inventory data, and approaches for operational monitoring of forest resources. USDA-ARS brings the perspective of operational users of the proposed products within the USDA, and also contributes expertise in assessing soil carbon using remote sensing. University of Maryland has considerable experience generating and distributing land-cover information to the science community, and has been an active participant in the ESIP Federation since its inception.

The principal investigator, Dr. Jeffrey Masek (GSFC-Code 923) will head the project and will also have the lead for algorithm development to map disturbance and forest-cover change. Dr. Forrest Hall (UMBC-Code 923) will have the lead for developing processing algorithms for Landsat surface reflectance. Mr Ed Masuoka (GSFC-Code 922) will have the lead for SEEDS liason and Mr. Robert Wolfe (GSFC-Code 922) for MODAPS modifications and algorithm implementation. Dr. David Harding (GSFC-Code 921) will act as a liason to the GLAS science and instrument teams and ensure GLAS data provision. Dr. Michael Lefsky (Colorado State University) will have the lead for processing and re-packaging GLAS data. Dr. Warren Cohen of the USDA Forest Service will have the lead for validation of the forest disturbance products using FIA ground inventory information. Dr. Donald Leckie of the Canadian Forest Service will assist in algorithm development for Canadian forest-cover change and disturbance. Dr. Paul Doraiswamy of the USDA, BARC center in Beltsville MD. will have the lead for algorithm development to generate land cover information for crop carbon cycle studies. Last but not least, Dr. John Townshend of the University of Maryland will have the lead for data distribution on the Maryland Global Land Cover Facility.

Given the scope of the project, and the number of participants, active coordination of efforts will be essential. Teleconferences will be held each week among all project participants to summarize progress, list open issues, and review upcoming milestones. An internal project web page will also be developed to distribute preliminary products and research results. Face-to-face meetings will take place in conjunction with semi-annual community workshops. Input from the user community will occur through the semi-annual workshops and a second set of monthly teleconferences with the Science Working Group. A kickoff workshop held as soon as practical (~two months) following project approval.

PERSONNEL

[Note: Selected publications are included in attached CV's for those members' names marked by an asterisk (*)]

Jeffrey G. Masek* (NASA GSFC - Principal Investigator): Dr. Masek is a Research Scientist in the Biospheric Sciences Branch at NASA GSFC. His research interests include mapping land-cover change in temperate environments, application of advanced computing to remote sensing, and satellite remote sensing. At GSFC, he serves as Deputy Project Scientist for the upcoming Landsat Data Continuity Mission. Dr. Masek has held previous positions at University of Maryland, Hughes Information Systems, and Cornell University. While at University of Maryland, he acted as project manager for the REALM Image Database system, which pioneered automated, large-area land-cover analyses through parallel processing of Landsat data, and was also Deputy Team Leader for the Landsat Science Team. At Hughes Information System, he managed the collaborative prototyping program for the EOSDIS Core System (ECS) project, which sought out and funded innovative earth science information prototypes from the academic community. Dr. Masek received a B.A. in Geology from Haverford College (1989) and a Ph.D. in Geological Sciences from Cornell University (1994).

Forrest G. Hall* (UMBC): Dr. Hall is Senior Scientist at the Joint Center for Earth Systems Technology at the University of Maryland, Baltimore County. At the NASA Goddard Space Flight Center's Laboratory for Terrestrial Physics he currently serves as Science Advisor in Goddard's Office of Global Carbon Studies. Dr. Hall recently co-lead with Dr. Chuck McClain of NASA GSFC, NASA's Carbon Cycle Science Study for NASA Headquarters that involved key carbon cycle scientists, agency leaders in carbon cycle science, as well as NASA Center scientists. Trained as a mathematical physicist. Dr. Hall has published over 30 papers in the last 10 years in areas ranging from remote sensing of terrestrial ecosystems to carbon cycle investigations. Dr. Hall has extensive technical management experience. In addition to being the BOREAS Project Manager, Principal Investigator for ISLSCP Initiative II, he has served as Project Manager of the FIFE Project, Chief of the Scene Analysis Branch at the Johnson Space Center, and Project Scientist of the Large Area Crop Inventory Project.

Edward Masuoka* (NASA GSFC): Mr. Masuoka is the Head of the Terrestrial Information Systems Branch at NASA's Goddard Space Flight Center. He leads the MODIS data processing support team, which is responsible for the development of MODIS Level 1 products and integrating and testing of over 70 higher-level science products for the MODIS instruments on the EOS Terra and Aqua spacecraft. He also is responsible for the development and operations of the MODIS Adaptive Processing System (MODAPS). Mr. Masuoka received a B.A. in Geology from Harvard University and a MS. in Geology from the University of Tennessee.

Robert Wolfe* (NASA GSFC) Mr. Wolfe is a Chief Scientist at Raytheon ITSS and works in the Terrestrial Information Systems Branch at NASA GSFC. He has over 22 years of experience working in the area of satellite remote sensing. Currently, he plays a key role within the MODIS Land science team by leading the overall land science data processing activities. He also leads the MODIS effort in the development and implementation of geolocation and gridding algorithms. He spent a number of years building both commercial and government production systems that perform geometric rectification of Landsat, SPOT and EOS-MODIS images. These systems use geometric models include both on-board navigation data from the spacecraft, instrument characteristics, ground control points and an earth model that included terrain. Mr. Wolfe received a B.S. in Mathematics and Physics from Bridgewater College (1980).

Warren Cohen* (U.S. Forest Service): Dr. Cohen is a Research Forester with the Pacific Northwest Research Station of the USDA Forest Service and Director of the Laboratory for Applications of Remote Sensing in Ecology at the Corvallis Forestry Sciences Lab in Oregon. He conducts research in remote sensing and related geographic and ecological sciences, with a primary focus on translating remote sensing data into useful ecological information, and has authored 58 publications in forestry and remote sensing. Dr. Cohen is also Assistant Professor (courtesy) in three departments at Oregon State and serves on the editorial board of Remote Sensing of the Environment. He holds a B.S. from Northern Arizona University, an M.S. from

University of Maine, and a Ph.D. from Colorado State University, all in Forest Science.

Michael Lefsky*: Dr. Lefsky is Assistant Professor of Forest Science at the Colorado State University, where he specializes in the application of lidar and passive optical remote sensing to forest structure assessments. He was previously Co-director of the Laboratory for Applications of Remote Sensing in Ecology at the Corvallis Forestry Sciences Lab (with W. B., Cohen). Dr. Lefsky received his B.A. from Bard College, and Ph.D. in Environmental Science from University of Virginia.

John Townshend (University of Maryland College Park). Dr. Townshend's research centers on the use of remote sensing and advanced computing methods for improvements in the characterization of regional and global land cover. He is currently chair of the Department of Geography at University of Maryland, College Park, and acts as PI for the UMD Global Land Cover Facility, a member of the ESIP Federation.

Donald Leckie (Canadian Forest Service): Donald G. Leckie received a Ph.D. degree specializing in remote sensing from the University of British Columbia in 1980. Dr. Leckie has been employed as a research scientist with the Canadian Forest Service at the Petawawa National Forestry Institute (PNFI), and more recently at the Pacific Forestry Centre, Victoria, B.C. Current research emphasis is on forest change detection and monitoring and use of high-resolution multispectral imagery for forest inventory. Dr. Leckie is also a leader of an initiative to develop a deforestation monitoring system for Kyoto Protocol carbon accounting.

Paul Doraiswamy (USDA-ARS): Dr. Doraiswamy is an Agricultural Meterologist in the Hydrology and Remote Sensing Laboratory, Agricultural Research Service (ARS), US Department of Agriculture (USDA). Hi research interests include crop condition and yield assessment using biophysical models and remotely sensed data. Dr. Doraiswamy leads the technology transfer of remote sensing to operational programs in the Foreign Agricultural Service (FAS) and National Agricultural Statistics Service (NASS) of USDA. Dr. Doraiswamy received his B.S. in Physics from Madras University (1967), an M.S. in Agricultural Meterology from University of Nebraska (1971), and a Ph.D. in Forest Meterology from the University of Washington (1977).

David J. Harding (NASA GSFC): Dr. Harding received a B.Sc. (1980) and Ph.D. (1988) in Geological Sciences from Cornell University. Since 1991 he has been a Staff Scientist in the Geodynamics Branch at NASA GSFC. He is director of the Laser Altimeter Processing Facility, which produced and distributes Shuttle Laser Altimeter and SLICER data sets. He has developed methods for measurement of vegetation canopy structure and topography using Lidar data. Dr. Harding is a member of the Shuttle Radar Topography Mapper (SRTM) science team, and is an associate member of the ICESat science team, for which he lead the definition of GLAS waveform processing algorithms, and is currently leading the validation of GLAS data products for vegetated landscapes.

Eric Vermote (NASA GSFC): Dr. Vermote is an associate research scientist in the Department of Geography at the University of Maryland working off site at Goddard Space Flight Center in code 922. He is a MODIS Science Team member responsible for the land surface reflectance product or the atmospheric correction algorithm, that is the input for higher level land standard product (LAI/FPAR, VI's,, BRDF/Albedo, Burned area). Dr. Vermote's research interests include in flight calibration of sensor, radiative transfer, aerosol retrieval and atmospheric correction in the solar spectrum and in the longwave. He received its Ph.D from the Laboratory for Atmospheric Optics at University of Lille (France) in 1990.

Alexei I. Lyapustin (NASA GSFC): received an MS/BS in physics from Moscow State University in 1987, and Ph.D. in Aerospace Remote Sensing from Space Research Institute, Moscow, Russia in 1991. Dr. Lyapustin actively works on the 3D radiative transfer over anisotropic non-homogeneous surfaces, developing the method of spherical harmonics. In the past two years, A. Lyapustin has been serving on VIIRS Operational Algorithm Team in the capacity of the NASA algorithm adviser.

Jan Gervin (NASA GSFC): Dr. Jan Gervin has been a remote sensing manager and research scientist with NASA for over 27 years, holding positions at Goddard Space Flight Center and Kennedy Space Center. She is currently Project Formulation Manager for NASA's Carbon Cycle Initiative, a multi-mission program to examine the seasonal, interannual and geographic distribution of carbon in Earth's atmosphere, oceans and on land. She received the BA in Physics with general honors from Bucknell University (1969), MS in Physics from the University of Florida (1971), and PhD in Engineering specializing in Remote Sensing Hydrology from the University of Maryland (1992). She has been elected to Phi Beta Kappa, Phi Kappa Phi and Sigma Xi, and has been the recipient of numerous professional awards, including the US Space Foundation Award for her work in analyzing medical imagery.

REFERENCES

Bateson, C.A., Asner, G.P, and Wessman, C.A., Endmember bundles: A new approach for incorporating end member variability into spectral mixture analysis, IEEE Trans. Geo. Rem. Sens., 38, 1083-1094.

Bosquet, P., P. Peylin, P. Ciais, C. Le Quere, P. Friedlingstein, P. Tans, 2001, Regional changes in carbon dioxide fluxes of land and oceans since 1980, Science 290, 1342.

Bruce, J. P., M. Frome, E. Haites, H. H. Janzen, R. Lal, and K. Paustian. 1998. Carbon Sequestration in Soil. Soil Water Conservations Society White Paper, 23 p.

Chavez, P.S., 1996, Image-based atmospheric corrections – revisited and improved, Photogrammetric Engineering and Remote Sensing, 62, 1025-1036.

Chavez, P.S., and D.J. MacKinnon, 1994, Automatic detection of vegetation changes in the Southwestern United States using remotely sensed images, Photogrammetric Engineering and Remote Sensing, 60, 571-583.

Ciais, P., P. P. Tans, J. W. C. White, M. Trolier, R. J. Francey, J. A. Berry, D. R. Randall, P. J. Sellers, J. G. Collatz, and D. S. Schimel, Partitioning of ocean and land uptake of CO2 as inferred by 13C measurements from the NOAA Climate Monitoring and Diagnostics Laboratory Global Air Sampling Network, J. Geophys. Res., 100, 5051-5070, 1995.

Chomentowski, W., B. Salas, & D. Skole, 1994. Landsat Pathfinder project advances deforestation mapping. GIS World. 7, 34-38.

Cohen, W.B., T.A. Spies, and M. Fiorella. 1995. Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, USA, International Journal of Remote Sensing, 16:721-746.)

Cole, C. V., K. Paustian, E. T. Elliott, A. K. Metherell, D. S. Ojima, and W. H. Parton. 1993. Analysis of agroecosystem carbon pools. Water, Air and Soil Pollution,70:357-371.

Collins, J.B. and C.E. Woodcock, 1996, An assessment of several linear change detection techniques for mapping forest mortality using multitemporal Landsat TM data, Remote Sens. Environ., 56, 66-77.

Crist, E.P., and R.C. Cicone, 1984, Application of the tasseled cap concept to simulated Thematic Mapper data, Photogrammetric Engineering and Remote Sensing, 50, 343-352.

Denning, A.S., I. Fung,and D.A. Randall, 1995. “Strong simulated meridional gradient of atmospheric CO2 due to seasonal exchange with the terresrial biota”, Nature, 37, 240-243.

Ekstrand, S., 1996, Landsat TM-based forest damage assessment: Correction for topographic effects, Photogrammetric Engineering and Remote Sensing, 62, 151-151.

Garcia-Haro, F.J., M.A. Gilabert, and J. Melia, 2001, Monitoring fire-affected areas using Thematic Mapper data, Int. J. Rem. Sens., 22, 533-549.

Gu, D., and A. Gillespie, 1998, Topographic normalization of Landsat TM images of forest based on subpixel sun-canopy-sensor geometry, Remote Sens. Environ., 64, 166-175.

Hall, F.G., D.B Botkin, D.E. Strebel, K.D. Woods, and S.J. Goetz, 1991a. Large-scale patterns of forest succession as determined by remote sensing, Ecology 72(2): 628-640.

Hall F.G., K.F .Huemmrich , S.J. Goetz, J.E. Nickeson, 1992. Remote Sensing of Surface Energy Balance: Successes, Failures and Unresolved Issues, J. Geophys. Res., 97(D17), pp 19061-19,091.

Hall, F.G., J.R. Townshend, and E.T. Engman, 1994. Status of remote sensing algorithms for estimation of land surface state parameters, Remote Sensing of Environment, 51:1, 138-157.

Hall, F. G., Y. E. Shimabukuro, and K. F. Huemmrich, Remote sensing of forest biophysical structure in boreal stands of Picea mariana using mixture decomposition and geometric reflectance models, Ecol. Appl., 5, 993-1013, 1995.

Hall, F.G., D.R. Peddle, and E.F. LeDrew, 1996. Remote Sensing of Biophysical Variables in Boreal Forest Stands of Picea Mariana. International Journal of Remote Sensing , 17:15, 3077-3081.

Hall, F.G., D. Knapp and K.F. Huemmerich, "Physically based classification and satellite mapping of biophysical characteristics in the southern boreal forest." J. Geophys. Res., BOREAS Special Issue, v. 102, n. 24, pp.29567, 1997.

Hansen, J.E., M. Sato, A. Lacis, R. Ruedy, I. Gegen, and E. Matthews, “Climate forcings in the industrial era, Proc. NAS, 95, 12753-12758, 1998.

Holben, B.N., T.F. Eck, I. Slutsker et al., 1998, AERONET – A federated instrument network and data archive for aerosol characterization, 66, 1-16.

Houghton, R.A., K.T. Lawrence, J.L. Hackler, and S. Brown, 2001, The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates, Global Change Biology, 7, 731-746.

Irish, R., 2000, Landsat7 Automatic Cloud Cover Assessment, in Algorithms for Multispectral, Hyperspectral, and Ultraspectral Imagery, SPIE v. 4049.

Jensen, J.R., 1996, Introductory Digital Image Processing, Upper Saddle River, NJ: Prentice-Hall, 316pp.

Justice, C. O., J. R. G. Townshend, E. F. Vermote, E. Masuoka, R. E. Wolfe, N. Saleous, D. P. Roy and J. T. Morisette, 2002, An overview of MODIS Land data processing and product status, Remote Sensing of Environment, 83, 3-15.

Kaufman, Y.J., Wald, A.E., Remer, L.A. et al., 1997, The MODIS 2.1-micron channel – correlation with visible reflectance for use in remote sensing of aerosol, IEEE Trans. Geosci. Remote Sens., 35, 1286-1296.

Kauth, R.J. and G.S. Thomas, 1976, The tasseled cap – a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat, in Proceedings, Symposium on Machine Processing of Remotely Sensed Data, West Lafayette, IN: LARS, 41-51.

Kern, J. S. 1994. Spatial patterns of soil organic carbon in the contiguous United States. Soil Sci. Soc. Am. J. 58: 439-455.

Kern, J.S., and Johnson, M.G., 1993, Conservation tillage impacts on national soil and atmospheric carbon levels, Soil Sci Am J., 57, 200-210.

Keeling, C. D., J. F. S. Chin, and T. P. Whorf, Increased activity of northern vegetation inferred from atmospheric CO2 measurements, Nature, 382, 146-149, 1996.

Koutsias, N. and Karteris, M., 2000, Burned area mapping using logistic regression modeling of a single post-fire Landsat-5 Thematic Mapper image, Int. J. Rem. Sens., 21, 673-687.

Lal, R., J. M.Kimble, R. F. Follett, and C. V. Cole. 1998. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Ann Arbor Press, Chelsea, MI, 128p.

Lefsky, M.A., W.B. Cohen, G.G. Parker, and D.J. Harding, 2002, Lidar remote sensing for ecosystem studies, Bioscience, 52, 19-30.

Liang, S., Fallahdal, H., Kalluri, S., et al., 1997, An operational atmospheric correction algorithm for Landsat Thematic Mapper imagery over the land, J. Geophys. Res., 102, 17,173-17,186.

Lyapustin, A.I., and Y.J. Kaufman, 2001, Role of adjacency effect in the remote sensing of aerosol, J. Geophys. Res., 106, 11909.

Lyapustin, A.I., and Y. Knyazikhin, 2002, Green's function method in the radiative transfer problem, II. Spatially heterogeneous anisotropic surface, Appl. Optics, 41, 5600-5606.

Malila,W.A., 1980, Change vector analysis: an approach for detecting forest changes with Landsat, Proceedings of Machine Processing of Remotely Sensed Data Symposium, West Lafayette, IN, LARS, 326-335.

Masek, J.G., C.T. Shock, and S.N Goward, 2001, Research Environment for Advanced Landsat Monitoring (REALM): A computational approach for Landsat-7 global science, Remote Sensing of the Environment, 78, 204-216.

Masek, J.G., G. Sun, D. Williams, and D. Jackson, Rates of forest cover change in Northeastern China during 1990-2000, in prep.

McClain, C. and others, 2002, Science and Observation Recommendations for Future NASA Carbon Cycle Research, NASA/TM-2002-210009.

Michalek, J.L., French, N.H.F., Kasischke, E.S., Johnson, R.D., Colwell, J.E., 2000, Using Landsat TM data to estimate carbon release from burned biomass in an Alaskan spruce forest complex, Int. J. Rem. Sens., 21, 323-338.

Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar, and R. R. Nemani, Increased plant growth in the northern high latitudes from 1981 to 1991, Nature, 386, 698-702, 1997.

Ouaidrari, H., and Vermote, E.F., 1999, Operational atmospheric correction of Landsat TM data, Remote Sens. Environ., 70, 4-15.

Pacala, S.W., and others, Consistent land-and atmosphere-based U.S. carbon sink estimates, Science, 292, 2316-2320, 2001.

Paustian, K., H. P. Collins, and E. A. Paul. 1997. Management controls on soil carbon. In: E. A. Paul, K. Paustian, E. T. Elliott, and C.V. Cole (eds). Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America. pp. 15-49, CRC Press, Boca Raton, FL, USA.

Paustian, K. J. Jastrow, M. Torn, R. Follett, M. Firestone. 1999. Agricultural and Grassland Ecosystems. In: Detailed descriptions of Ecosystems and research and development needs. Proceeding; Workshop on Research and Development Priorities for Carbon. September 14-15, 1999, Gaithersburg, MD. Appendix B, B7-12.

Peddle, D.R., F.G. Hall and E.F. LeDrew, 1996. Spectral Mixture Analysis and Geometric Optical Reflectance Modeling of Boreal Forest Biophysical Structure. Remote Sensing of Environment.

RussellSmith, J., Ryan, P.G., and Durieu, R., 1997, A Landsat MSS-derived fire history of Kakadu National Park, monsoonal Northern Australia: Seasonal extent, frequency, and patchiness, J. Appl., Ecol., 34, 748-766.

Schimel, D., 1995, Terrestrial ecosystems and the carbon cycle, Global Change Biology, 1, 77-91.

Schott, J.R., Salvaggio, C., and Volchock, W.J., 1988, Radiometric scene normalization using pseudoinvariant features, Remote Sens. Environ., 26.

Skole, D.L., and C.J. Tucker, 1993, Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, Science, 260, 1905-1910.

Song C, Woodcock CE, Seto KC, Lenny, MP, Macomber, M., 2001, Classification and change detection using Landsat TM data: When and how to correct atmospheric effects?, Remote Sens. Environ., 75, 230-244.

Steyaert, L.T., F.G. Hall, and T.R. Loveland, 1997. Land cover mapping, fire-regeneration, and scaling studies in the Canadian boreal forest with 1-KM AVHRR and Landsat TM Data, J. Geophysical Research, 102:29581-29598

Tans, P.P., I.Y. Fung, and T.Takahashi, 1990. "Observational constraints on the global atmosphere CO_2 budget", Science, 247, 1431-1438.

Townshend,, J.R.G., and C.O. Justice, 1988, Selecting the spatial resolution of satellite sensors required for global monitoring of land transformations, Int. J. Remote Sens., 9, 187-236.

Townshend JRG, Huang C, Kalluri SNV, Defries, R., Liang, S., Kang, Y., 2000, Beware of per-pixel characterization of land cover, Int. J. Rem. Sens., 21, 839-843.

Tucker, C.J., and J.R.G. Townshend, 2000, Strategies for monitoring tropical deforestation using satellite data, Int. J. Remote Sens., 21, 1461-1471.

Vermote, E.F., et al., 1997, Atmospheric correction of visible to middle-infrared EOS-MODIS data over land surfaces: Background, operational algorithm, and validation, J. Geophys. Res., 102, 17131-17141.

Watson, R.T. and others, 2001, Climate Change 2001: Synthesis Report. Geneva: IPCC, pp. 184.

Waltman, S.W. and N.B. Bliss. 1997. Estimates of SOC content for the U.S. USDA/ NRCS, Lincoln, NE.

Wen, G., S.-C. Tsay, R.F. Cahalan, and L. Orepolulos, 1999, Path radiance technique for retrieving aerosol optical thickness over land, J. Geophys. Res., 104, 31,321-31,332.

Wofsy, S.C. and R.C. Harriss, 2002: The North American Carbon Program (NACP). Report of the NACP Committee of the U.S. Interagency Carbon Cycle Science Program. Washington, DC: US Global Change Research Program.